Díaz-Álvarez, A., Rubio-López, Á., Santiuste, C., & Miguélez, M. H. (2018). Experimental analysis of drilling induced damage in biocomposites. Textile Research Journal, 88(22), 2544–2558.

https://doi.org/10.1177/0040517517725118

EXPERIMENTAL ANALYSIS OF DRILLING INDUCED DAMAGE IN BIOCOMPOSITES

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Abstract.

This paper focuses on the analysis of drilling induced damage on biocomposite (woven fibres of cotton, flax and jute combined with Polylactic acid, PLA, as matrix). Main contribution of this work is the analysis of the influence of cutting parameters and drill geometry on fully biodegradable composites based on two different types of Polylactic acid and different fibres types. The damaged area was studied both at hole entry and exit. Contrarily to the behaviour commonly observed when drilling conventional composites, delamination was negligible. Hole entry and exit damage were analysed quantified in terms of fraying extension being the dominant. The damage extension was found to be dependent on the matrix and fibre type and drill geometry. The combination between cotton fibre and small drill point angle showed the lowest level of damage. On the other hand, composite reinforced with flax fibres (those exhibited the highest tensile strength) presented the greatest damage extension, increasing with the number of layers of the composite. The matrix based on polymer 10361D PLA, recommended for natural fibres because of the better interface cohesion, resulted in reduced fraying. Concerning the influence of cutting parameters, damage decreased when increasing cutting speed and feed rate.

Keywords: Composites; Natural Fibres; Drilling; Damage; Waste reduction; Testing

NOMENCLATURE	
CFRP	*Carbon fiber reinforced polymer*
HSS	*High-speed steel*
SC	*Solid Carbide*
RTM	*Resin transfer molding process*
PLA	*Polylactic acid*
PLA 3	*3260HP Polylactic acid*
PLA 10	*10361D Polylactic acid*
PJ	*Plain weave jute*
BC	*Basket weave cotton*
BF	*Basket weave flax*
PF	*Plain weave flax*
Rh	*Relative humidity*
V	*Cutting speed*
f	*Feed rate*
DOE	*Design of Experiments*
Fd	*Damage factor*
SEM-EDS	*Scanning Electron Microscopy*

1. Introduction

Drilling is an operation commonly required for mechanical joining of composite components [1]. Induced damage is one of the undesired effects of drilling mainly due to the use of inadequate cutting parameters or worn drill and has received extensive attention in the literature [2]. There are numerous studies focused on induced damage during machining of carbon and glass fibre composites since it is a common cause of component rejection. Induced damage during drilling of composite is mainly influenced by cutting parameters and drill geometry, including geometrical variations due to wear progression [3,4]. In the case of carbon fiber reinforced polymer (CFRP) delamination is the main damage mechanism, increasing with feed rate that is the most influencing factor [5,6,7]. The effect of cutting speed is not clear and seems to have a cross effect with thickness and spindle speed. Davim et al. [8,9] showed that delamination increased with cutting speed during conventional drilling while Gaitonde et al. [10] showed an opposite effect.

Cutting speed shows much lower influence than feed rate and in some cases it was found to be negligible [11].

In the last few years, natural fibres based composites have been considered promising materials to replace traditional composites [12]. In terms of matrices, non-biodegradable polymeric materials (such as epoxy, polyethylene or polypropylene) are typically used with natural fibres [13]. However, biodegradable matrices can also be used in order to obtain 100 % eco-sustainable composites [14]. The introduction of fully biodegradable composites reduces the use of non-biodegradable materials and non-renewable resources. Moreover, energy needed to produce natural fibres is really reduced (for instance, 4 GJ/ton in plant fibres and 30 GJ/ton for fibreglass [15]). Moreover, health and environment hazards during production and handling of biodegradable composites are decreased comparing with synthetic fibres. It is also provided the opportunity to use waste from mills and farms [16] which in turn can be reused after the biocomposite lifecycle [17]. These advantages make biocomposites a real alternative to traditional composites [18,19].

On the other hand, some of the disadvantages of biodegradable composite are lower mechanical properties [14], low resistance to high temperatures [20], high flammability [21], and poor adhesion between polymeric matrix and fibres [22]. Although the balance between benefits and drawbacks should be taken into account, biocomposites are suitable for numerous industrial applications as car panels [23,24], boats [25] or electronics applications [26] for instance.

There is a lack of research works focused on drilling of fully biodegradable composites compared to the attention focused on drilling conventional composites [27]. Main contributions concerning the analysis of drilling of composites manufactured with natural fibres and non-degradable matrixes as polyester or epoxy are briefly summarized in the following paragraphs.

Sidharan and Muthukrishnan [28] drilled a sisal/polyester composite with twist drill (point angle 118º, diameter 6 mm) in a Vertical Machining Centre observing that induced damage (mainly delamination) increased with feed rate and cutting speed.

Abilash and Sivapragash [29] analysed drilling of composite based on polyester matrix and bamboo fibres, finding that feed rate is the key parameter to control induced delamination.

Ramesh et al. [30] carried out a parametric analysis, determining that fibre breakage was the main failure mode and finding that damage extension increases with feed rate and the convenience of using solid carbide (SC) drill bit instead of high-speed steel (HSS).

Athijayamani et al. [31] proved that an alkali treatment during 8 hours on 30% wt. sisal fibres combined with polyester improves the drilled hole quality.

Nasir et al. [32] manufactured a flax/epoxy composite by resin transfer molding process (RTM), they found that induced damage increases with feed rate but decreases with cutting speed.

According to these studies the influence of cutting parameters and the failure modes are related to the manufacturing route and the matrix type. None of these works analysed the behaviour of fully biodegradable composites manufactured with natural polymers. Only the work of Bajpai et al. [33] focused on drilling of fully biodegradable composites. They manufactured Polylactid Acid (PLA) based biocomposites reinforced with sisal and Grewia optiva fibres and analysed the influence of drill geometry on cutting forces and push-out damage area. However, more studies are necessary to get a deeper understanding of the induced damage during drilling of biodegradable composites.

The aim of this work is developing a parametric study focused on drilling induced damage on fully biodegradable composites during drilling. Cotton, flax and jute woven fibres were combined with PLA matrix and the biocomposites were manufactured by compression moulding method. The influence of matrix (two different PLA), reinforcement (three composite fibres), drill geometry (diameter and drill point angle) and plate thickness is analysed. Interesting results, such as the occurrence of fraying as the dominant damage mechanism and the relationships between tensile strength and damage are explained in the following sections. There are two sustainability concepts included in the goal of the paper. Firstly, the implementation of fully-biodegradable composites in industry replacing oil based resins by organic polymers. Secondly; the improvement of the drilling process selecting proper cutting parameters increasing the quality of the final product and reducing machining costs.

2. Experimental work

This section includes the description of the manufacturing route to obtain fully biodegradable composites, the explanation of the drilling test procedure including machining device and cutting parameters, and the evaluation of damage extension.

2.1.Manufacturing route

Fully biodegradable composites were manufactured using compression moulding method. Four different woven fibres made from yarns were used as reinforcement: plain weave jute (PJ); basket weave (2x1) cotton (BC), basket weave (2x1) flax (BF); and plain weave flax (PF), which were cut into 150x150 mm plates. No chemical pre-treatment was applied to woven fibres. Information about the yarn diameter, woven thickness and areal density is shown in Table 1.

Matrix was PLA being a thermoplastic resin, acquired in pellets form. Two types of PLA polymer were used: the 3260HP (PLA 3) and the 10361D (PLA 10), both provided by Nature works LLC. The 3260HP PLA is aimed to an extrusion process whereas the 10361D PLA is specifically designed as a binder of natural fibres. The PLA density is 1.24 g/cm^3 and the melting temperature is around 145-170ºC.

Fabric	*Yarn linear density (tex)*	*Woven thickness (mm)*	*Areal density (gr/m^2)*	*Warp crimp ratio (%)*	*Weft crimp ratio (%)*
BF	*127-135*	*0.94*	*463,3*	*2*	*7*
PF	*102-109*	*0,45*	*295,3*	*5*	*12*
PJ	*245-231*	*0.88*	*340.2*	*3*	*4*
BC	*142-136*	*0.83*	*409.5*	*3*	*11*

Table 1. Information about fabrics: yarn linear density, woven thickness, areal density and crimp ratios in warp and weft directions.

Compression moulding method included several steps graphically described in Fig.1. PLA pellets were maintained in the oven at 95º for 4 hours before they were placed between the thermo-heated plates to obtain a PLA films. PLA pellets are placed between two thermo-heated plates at a temperature equal to 185ºC during 3 minutes in order to obtain a uniform film. The dimensions of the PLA films were 160 x 200 mm^2. Then, the matrix films are stacked alternatively with woven plies and were dried with natural fibres for 30 minutes. The stacked plies are placed between the thermo-heated plates, also at temperature 185ºC. After a pre-heating time of 2 minutes, pressure of 16 MPa is applied during 3 minutes using a universal testing machine Servosis ME-404/100 + PCD-1065. Finally, the biocomposite panels were dried at room temperature.

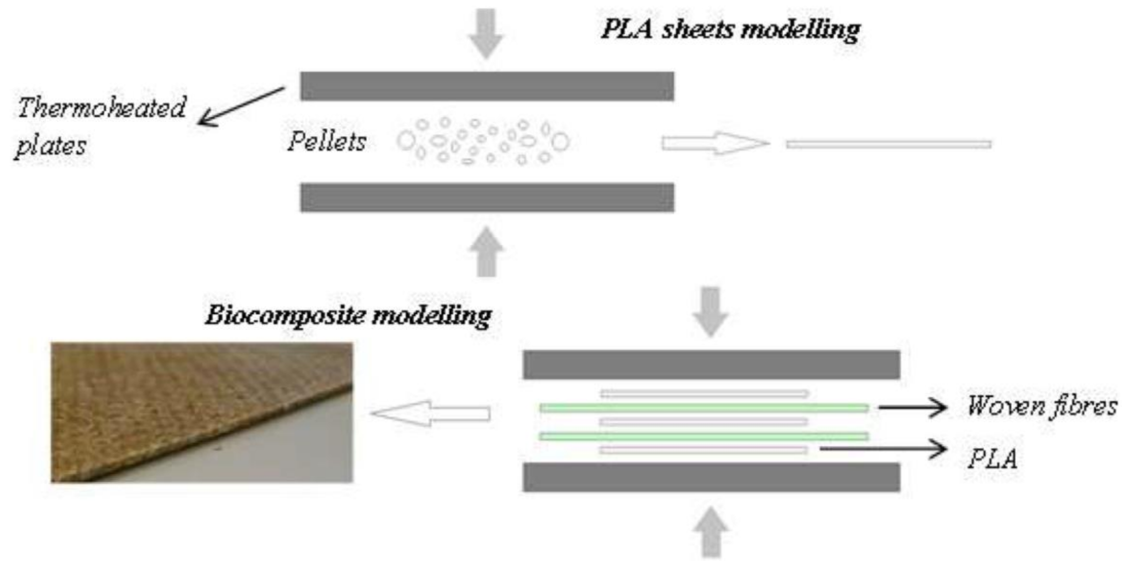

Figure 1. Scheme of the manufacturing process to obtain the biocomposite from natural fibres woven plies and PLA in pellets.

All the composites were manufactured with 2, 3 and 4 layers with the objective of analysing the influence of thickness on the induced damage during drilling. Woven fibres and PLA plies were maintained in an oven under 95ºC during 30 minutes before the compression moulding processing to remove water content. All the materials were stored in stable constant conditions of 46% relative humidity (RH) and 20ºC before and after the manufacturing process to control the environmental conditions influence.

The biocomposites presented a resultant 65% weight reinforcement ratio, which is considered an optimum value as it was reported by Ochi [34]. The weight ratio was calculated assuming a constant value of areal density in the natural fibre woven plies. Different measurements of this value were conducted and an excellent repeatability was found. Then, the volume and the weight of the composite specimens were measured to find the weight ratio. A maximum difference of 2% was admitted thus some specimens were discarded. The weight ratio for different materials was controlled using PLA films with different thicknesses. The resulting fibre volume fractions, calculated according to

ASTM D2584, were 58.6% for flax composites, 59.5% for cotton composites and 60.2% for jute composites.

Tensile strength of each manufactured composite is summarized in Table 2. Tensile tests were performed in a universal test machine Instron 8516 according to ASTM D3039. Samples were cut in rectangular specimens of 120 x 30 mm. Tensile strength was determined with the peak force of the force-displacement curve. More details concerning the manufacturing process and mechanical properties can be found in [14].

Material	***Tensile Strength (MPa)***	***Standard Deviation (MPa)***	***Elastic Modulus (GPa)***	***Ultimate strain***
BF/PLA 3	*116.3*	*2.42*	*7.96*	*0.069*
BF/PLA 10	*104.0*	*4.71*	*7.84*	*0.061*
PF/PLA 10	*96.9*	*3.80*	*8.50*	*0.065*
PJ/PLA 10	*66.6*	*8.22*	*7.38*	*0.033*
BC/PLA 10	*62.4*	*3.70*	*12.34*	*0.104*

Table 2. Tensile strength of the manufactured biocomposites [14].

2.2.Drilling test.

The drilling tests were carried out in a B500 KONDIA machining centre in dry conditions. A dynamometer (Kistler 9123C) was implemented in the machine tool (see Fig.2) to measure thrust force and torque on the rotating tool. Drilling operations were carried out into a confining device allowing air entrance and connected to a vacuum with the aim of collecting the dust fibres generated during chip removal.

Three different values of cutting speed (***V***), ranging from 15 to 25 m/min, and three values of feed rates (***f***), ranging from 0.03 mm/rev to 0.12 mm/rev, were analysed. Two different drill geometries were studied since drill point angle is a key parameter in damage generation when drilling composites. Firstly, a HSS drill bit with 118º point angle, denoted Drill-A (3, 5 and 6 mm diameter, see Fig.3a). Secondly, a custom HSS drill was manufactured for this study with 80º point angle and 40º helix angle, denoted Drill-B (6 mm diameter, see Fig.3b). The cutting angles on Drill-B were selected close to the optimum point angle recommended for glass/carbon composites [4]. These cutting parameters were stated in the range commonly defined for natural fibres based composites (see for instance [33]).

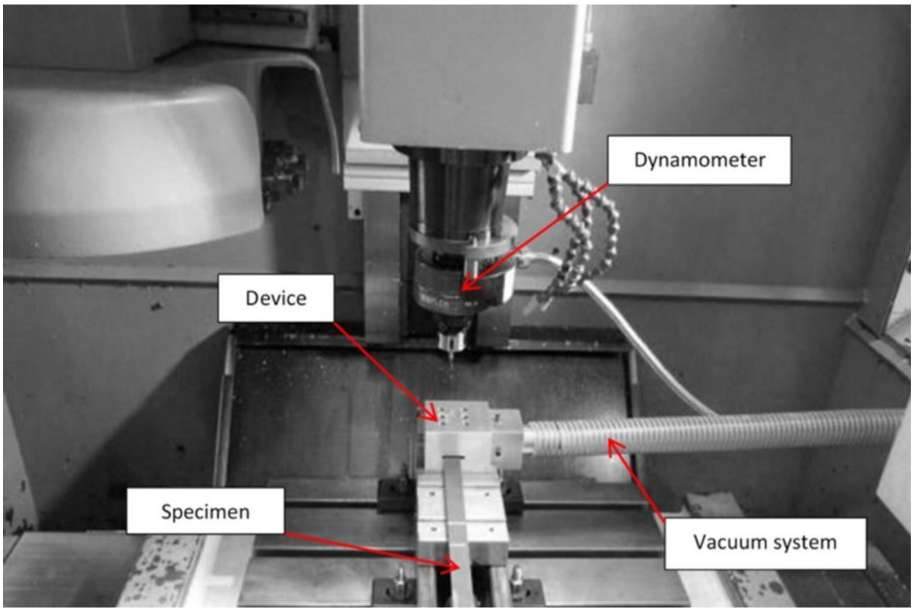

Figure 2. Machining centre used for drilling tests, showing Dynamometer Kistler 9123C and vacuum system for chip collection.

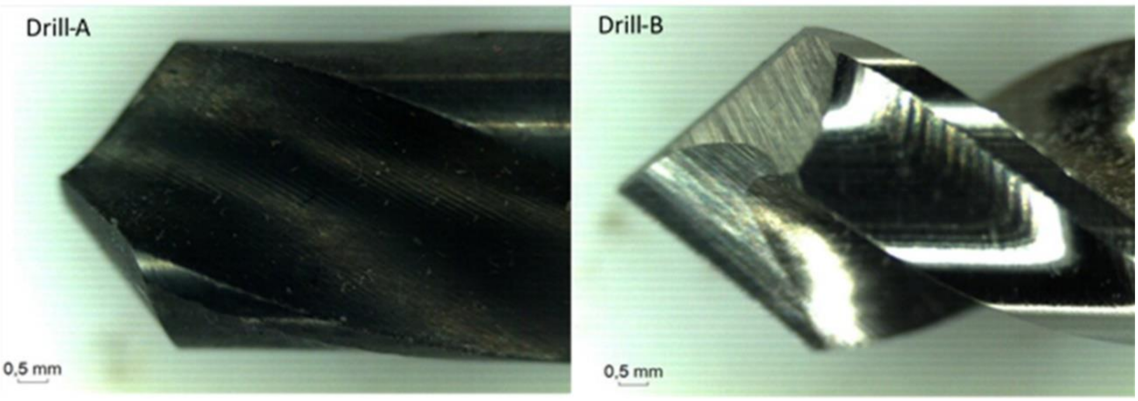

Figure 3. Drill-A: HSS drill (118º) and Drill-B: Custom HSS drill (80º).

Damage factor

Damage extension was quantified in terms of the damage factor (F_d) defined as the ratio between the maximum diameter of the damaged area and the nominal diameter of the drill. Damaged area was obtained from the analysis of the hole images captured with a stereo microscope (Optika SZR).

The evaluation of F_d is illustrated in Fig. 4a, where the difference between the nominal diameter and the maximum damaged diameter can be observed. The damage factor was evaluated both at the entrance (peel up) and the exit (push out) of the drilled hole. Fig. 4 shows fibres breakage originating fraying that is the main failure mode observed when drilling the biocomposites studied in this work. On the other hand, although delamination is the dominant damage mode observed in conventional fibre composites [2] in the case of the materials analysed in this work there is no evidence of this phenomenon. Fig.5 shows a scheme to illustrate the difference between delamination and frying. The absence of delamination can be stated looking to the Fig. 4b, where it can be observed no evidence of break between layers neither at the entrance nor at the exit of the drill along the thickness of the biocomposites, appearing only fraying as the main defect during drilling. Similar behaviour was observed in all cases analysed.

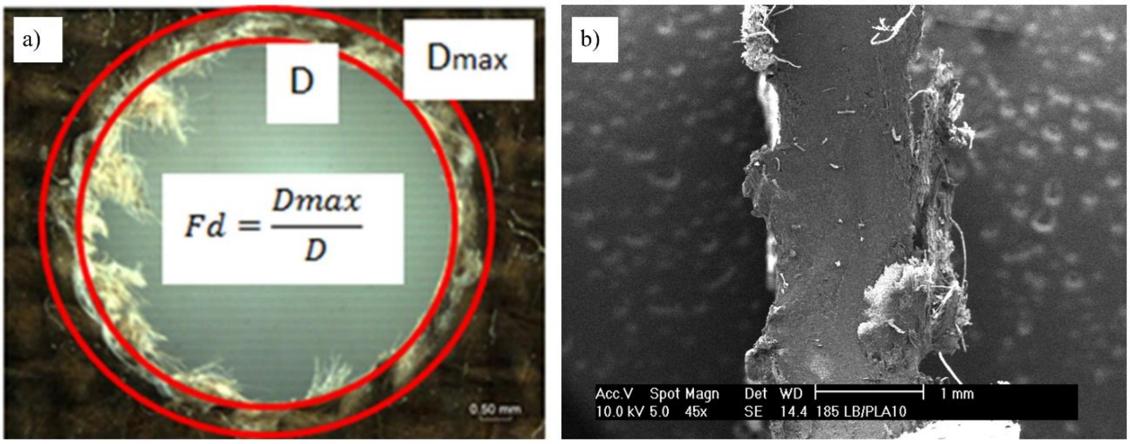

Figure 4. a) Damage factor Fd calculation (2 layers Jute and 10361D PLA, drilled with drill-A); b) SEM- EDS image of transversal section of the drilled hole (2 layers basket weave flax (BF) and 10361D PLA), drilled with drill-B at cutting speed 20 m/min and feed rate 0.12 mm/rev.

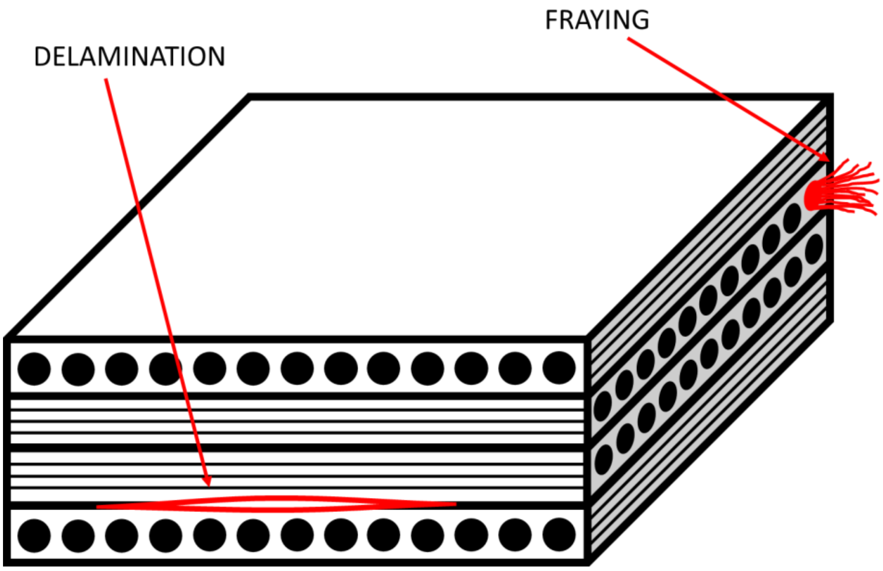

Figure 5. Scheme of the main induced damage mechanisms during drilling of composites.

3. Results and discussion

The parameters of drilling tests and results in terms of damage factor are summarized in Table 3. The parameters included in the analysis are: combination of fibre and matrix materials, laminate thickness, drill bit, drill diameter, cutting speed and feed rate. Three drilling tests were conducted for each configuration, the repeatability of the results was excellent and standard deviation was negligible.

Fibre/Matrix	*Layers*	*Thickness [mm]*	*Ø [mm]*	*V [m/min]*	*f [mm/rev]*	*Peel up [mm]*	*Peel out [mm]*	*Test*
BC/PLA 10	2	1.53	6	15	0,06	1,05 *(1.04)*	1,06 *(1.05)*	1
				20	0,03	1,04 *(1.04)*	1,05 *(1.06)*	2
					0,06	1,02 *(1.03)*	1,04 *(1.05)*	3
					0,12	1,02 *(1.02)*	1,03 *(1.03)*	4
				25	0,06	1,03 *(1.02)*	1,03 *(1.04)*	5
PJ/PLA 10		1.25		15	0,06	1,05 *(1.03)*	1,07 *(1.05)*	6
				20	0,03	1,05 *(1.04)*	1,07 *(1.05)*	7
					0,06	1,04 *(1.03)*	1,06 *(1.04)*	8
					0,12	1,03 *(1.03)*	1,04 *(1.05)*	9
				25	0,06	1,04 *(1.03)*	1,06 *(1.03)*	10
PF/PLA 10		1.05		15	0,06	1,07 *(1.05)*	1,08 *(1.07)*	11
				20	0,03	1,06 *(1.06)*	1,08 *(1.08)*	12
					0,06	1,05 *(1.05)*	1,06 *(1.06)*	13
					0,12	1,04 *(1.04)*	1,05 *(1.05)*	14
				25	0,06	1,05 *(1.04)*	1,07 *(1.05)*	15
BF/PLA 10		1.04		15	0,06	1,09 *(1.05)*	1,11 *(1.06)*	16
				20	0,03	1,07 *(1.05)*	1,08 *(1.06)*	17
					0,06	1,05 *(1.04)*	1,08 *(1.05)*	18
					0,12	1,03 *(1.03)*	1,05 *(1.04)*	19
				25	0,06	1,04 *(1.03)*	1,06 *(1.04)*	20
BF/PLA 3				15	0,06	1,11	1,12	21
				20	0,03	1,10	1,13	22
					0,06	1,09	1,10	23
					0,12	1,05	1,08	24
				25	0,06	1,07	1,09	25
BF/PLA 10	3	2.14		20	0,06	1,05 *(1.04)*	1,08 *(1.05)*	26
BC/PLA 10		2			0,06	1,03 *(1.03)*	1,05 *(1.04)*	27
BF/PLA 10	4	2.68			0,06	1,06 *(1.04)*	1,11 *(1.06)*	28
BC/PLA 10		2.85			0,06	1,04 *(1.04)*	1,08 *(1.06)*	29
BF/PLA 10		2.68	5		0,06	1,06	1,11	30
BC/PLA 10		2.85			0,06	1,04	1,07	31

BF/PLA 10	2.68	3	0,06	1,06	1,10	32
BC/PLA 10	2.85		0,06	1,03	1,06	33

Table 3. Damage Factor, Fd, at hole entrance (peel up) and exit (push out) for drill A and (B) measured in each test depending on woven fibres, PLA type, thickness, and cutting parameters.

A general trend can be observed: push out damage is greater than peel up damage at the entrance in all tests. These results are in agreement with the behaviour observed when drilling CFRPs. Davim et al. [5] explained this phenomenon due to the compression of the plate leading to higher values of forces during drilling. The results for the drill-B showed lower damage factor than drill-A type due to the smaller point angle of drill-B. Higher values of drill point angle are commonly related with increased thrust forces and enhanced delamination at the hole exit in drilling of conventional composites [35,36].

There are clear differences between results showed in Table 3 and those reported by other authors in natural based composited manufactured with non-degradable matrices, see Table 4. Damage factors obtained in this work are lower compared with drilling induced damage in composites manufactured with non-degradable matrixes. On the other hand, it is worth noting that the main damage mechanism reported in the second case is delamination. The consequences of damage in further service behaviour of the component can be magnified because of stress concentration around the drilled hole influencing fatigue behaviour and as a result, service life of the component.

Drill Geometry	*Fibre/Matrix*	*Reference*	*Thickness/Cutting Parameters*	*Max. Damage Factor (Fd)*
Twist Drill 	Jute/Polyester	Sridharana et al. [31]	Thickness: 3.75 mm; Diameter: 6 mm; Feed: 0.03, 0.06, 0.09, 0.12 mm/rev; Cutting Speed: 9.42, 15.072, 20.724, 26.376 m/min.	Entrance: 1.24 Exit: 1.29
	Bamboo/Polyester	Abilash et al. [32]	Diameter: 4, 6, 8 mm; Feed: 0.036, 0.03, 0.025 mm/rev; Cutting Speed: 12.56, 32.42, 68.36 m/min.	Entrance: 1.14 Exit: 1.23
	Flax/Epoxy	Nasir et al. [35]	Diameter: 8 mm; Feed: 0.16, 0.24 mm/rev; Cutting Speed: 150.80, 301.59 m/min.	Entrance: 1.29 Exit: 1.21
	Grewia optiva-Sisal/PLA	Bajpai et al. [36]	Thickness: 5 mm. Diameter: 8 mm; Feed: 0.05, 0.12 y 0.19 mm/rev; Cutting Speed: 45.24, 90.48, 104.74 m/min.	Exit: 1.5
	Jute;Cotton;Flax/ PLA	Present Study	Thickness: 1.04, 1.05, 1.25, 1.53, 2, 2.14, 2.68, 2.85 mm. Diameter: 6 mm; Feed: 0.03, 0.06 y 0.12 mm/rev; Cutting Speed: 15, 20, 25 m/min.	Entrance: 1.11 Exit: 1.13

Table 4. Comparative table between the obtained maximum damage factor (Fd) and those obtained from literature.

The influence of the different parameters on the machinability of the biocomposites is analysed in the following subsections. The drilling operation is evaluated in terms of thrust force and damage factor. The enhancement of thrust force is related to delamination increase when drilling conventional composites (see for instance [11,35]).

3.1. Cutting speed

The influence of cutting speed is analysed through the comparison of the tests denoted with numbers 1, 3, 5, 6, 8, 10, 11, 13, 15, 16, 18, 20, 21, 23 and 25 in Table 3.These tests were carried out on composites consisting of 2 layers with nominal drill diameter equal to 6 mm and at constant feed rate equal to 0.06 mm/rev.

Peel up and push out damage factor against cutting speed are graphically represented in Fig.6 for the different types of composites analysed. It is observed a general trend for all cases tested: damage decreases with cutting speed. This trend agree with the results of Nasir et al. [32] when drilling flax/epoxy composites. However, this trend is different to that observed in conventional composites where the effect of cutting speed is much lower than the influence of feed rate. Moreover, in recent works of the authors, it was reported the influence of drill geometry on the sensibility of delamination in CFRPs with cutting speed, observing negligible or significant influence for different drills configuration [11,35]. BF/PLA10 composites showed the higher variation of induced damage with cutting speed, mainly in the case of Drill-A. This effect can be attributed to a greater influence of strain-rate on the mechanical behaviour of this composite [37].

Fig.7 shows thrust forces as a function of cutting speed for all cases analysed. Thrust forces generated by the Drill-A were higher than those obtained with Drill-B. This is due to the higher point angle of Drill-A (118º) compared to Drill-B (80º). Thus a small point angle can be recommended to machine biocomposites in order to moderate thrust force (the same behaviour has been reported for conventional composites). However, the influence of cutting speed is found to be negligible on thrust force, although Fig.6 shows a clear influence of cutting speed on induced damage. This is due to the nature of damage evaluated mainly consisting of fraying commonly decreasing with cutting speed due to the cleaner cut produced at higher velocities. However, in conventional composites the dominant damage mode is delamination and the effect of thrust force is directly related with damage.

The analysis of Fig. 6 shows the influence of weave patterns on induced damages. Induced damage on specimens with plain weave (PF and PJ) is less sensitive to cutting speed than specimens with basket weave (BF and BC). However, there are numerous parameters that can influence on these results as yarn linear density and crimp ratios.

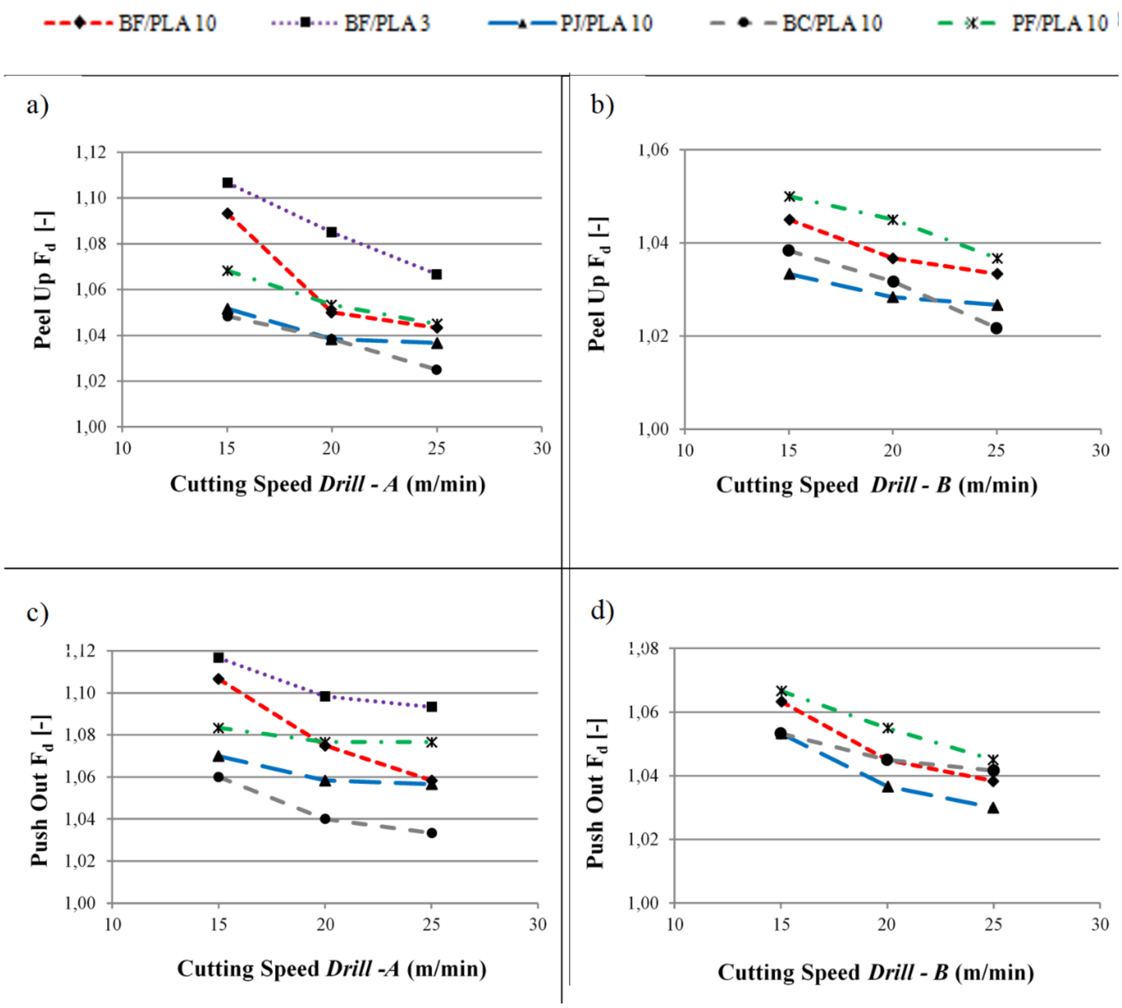

Figure 6. Damage factor vs cutting speed for all composites analysed (BF/PLA10, BK/PLA3, PJ/PLA10, BC/PLA10, PF/PLA10). a) Peel up obtained with Drill-A, b) Peel up obtained with Drill-B, c) Push out obtained with Drill-A and d) Push out obtained with Drill-B.

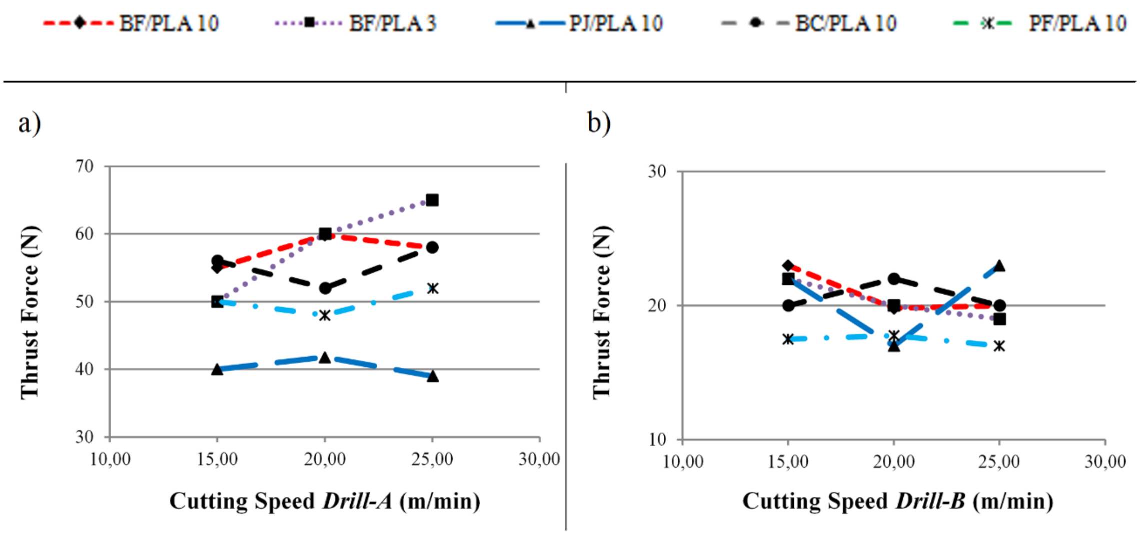

Figure 7. Thrust forces vs cutting speed for all composites analysed (BF/PLA10, BK/PLA3, PJ/PLA10, BC/PLA10, PF/PLA10).a) Drill-A, b) Drill-B.

Feed rate

The influence of feed rate was observed analysing the tests denoted 2-4, 7-9, 12-14, 17-19, 22-24 in Table 3. These tests were carried out on composites manufactured with 2 layers with nominal drill diameter equal to 6 mm and at constant cutting speed equal to 20 m/min.

Fig.8 shows peel up and push out damage factor as a function of feed rate for the different types of composites analysed. It is clearly observed that induced damage decreases with feed rate. However, the results found in the scientific literature indicates that induced damages increases with feed rate when machining carbon fibre composites [2,4,5], sisal/polyester composites [23], and flax/epoxy composites [29]. The disagreement is related to the different dominant failure modes, other authors identified delamination as the main failure mode while fibre breakage leading to fraying was the dominant failure mode found in the present work. Non-destructive tests were conducted using C-Scan ultrasonic inspection with the aim of confirming that delamination was not induced during drilling tests. In addition, a strong influence of strain rate on mechanical properties is well known in biocomposites [37]. The significant increment of biocomposites stiffness with strain rate can explain the increased brittle behaviour at high feed rates.

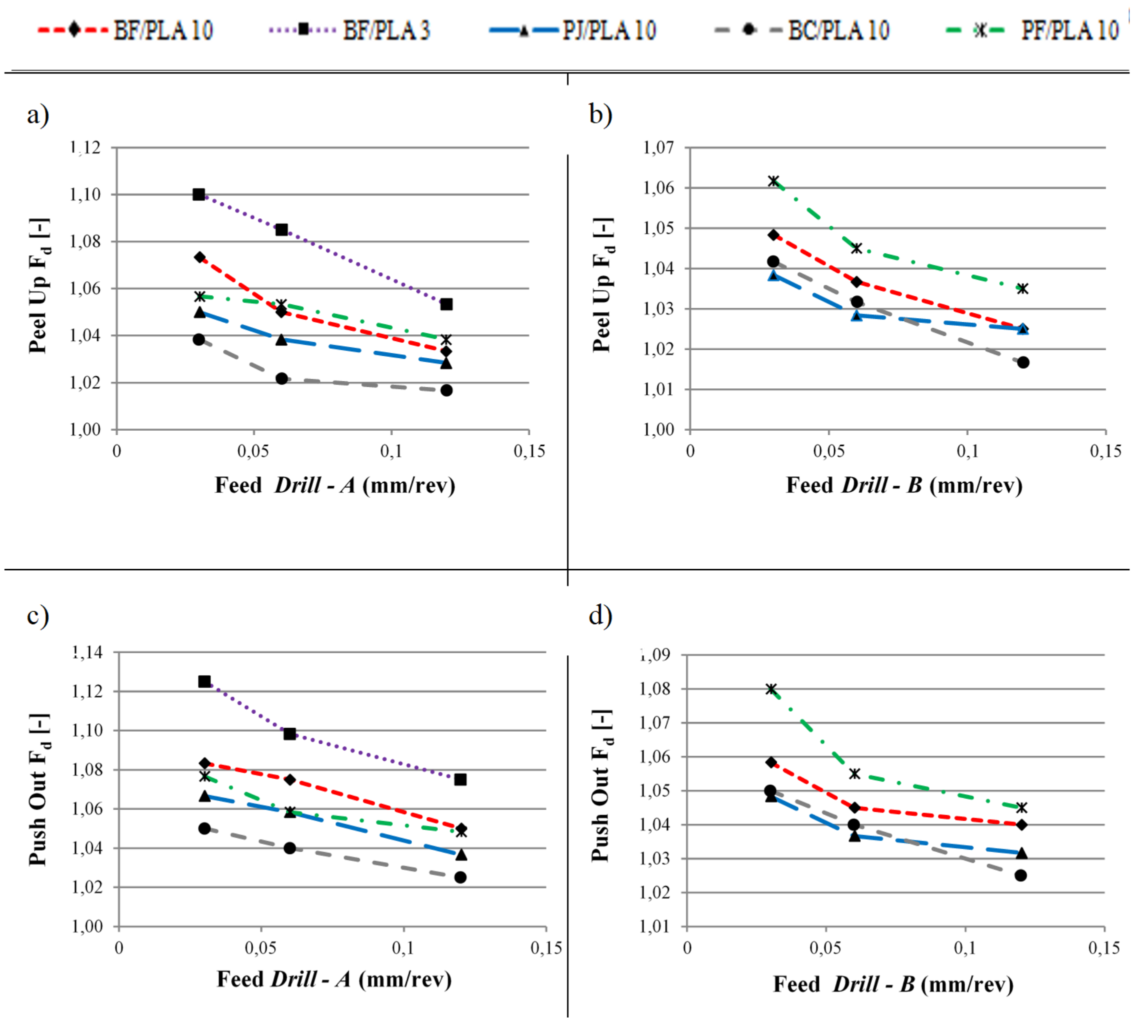

Figure 8. Damage factor vs feed rate for all composites analysed (BF/PLA10, BK/PLA3, PJ/PLA10, BC/PLA10, PF/PLA10). a) Peel up obtained with Drill-A, b) Peel up obtained with Drill-B, c) Push out obtained with Drill-A and d) Push out obtained with Drill-B.

Thrust forces as a function of feed rate are summarized in Fig.9. Thrust force increases with feed rate, as expected. In all cases thrust forces induced by Drill-A were higher than those produced by Drill-B. As it was explained previously, this fact can be explained by the higher point angle of Drill-A leading to lower values of thrust force independently of feed rate.

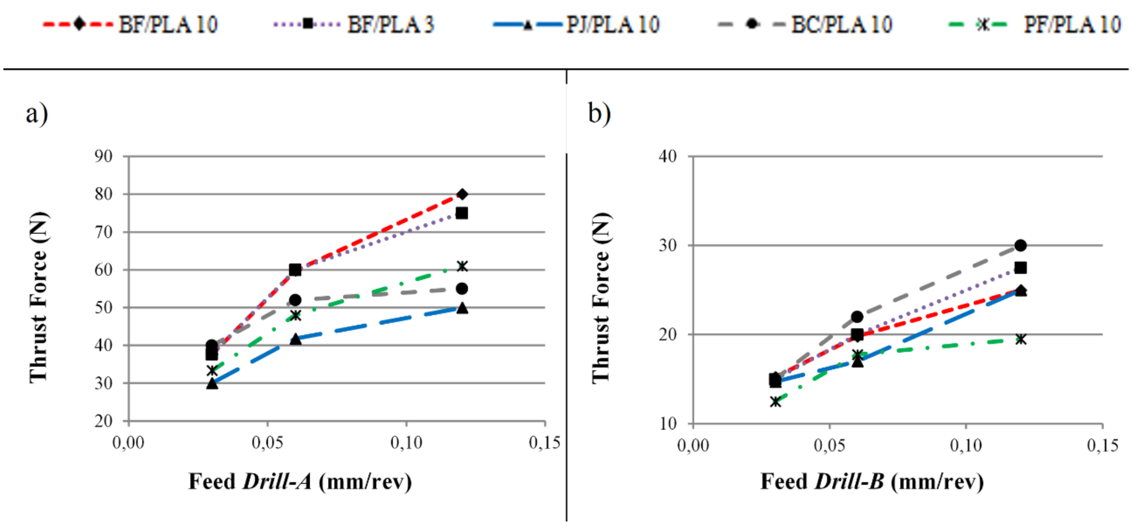

Figure 9. Thrust forces vs feed rate for all composites analysed (BF/PLA10, BK/PLA3, PJ/PLA10, BC/PLA10, PF/PLA10).a) Drill-A, b) Drill-B.

Moreover, the samples were observed using SEM-EDS through a transversal cutting along the drilled hole in order to analyse the damage generated at the hole wall depending on feed rate. It was observed that for all materials hole surface quality is enhanced with the feed rate. Fig.10 shows an example of hole quality for the composite consisting of basket weave flax (BF) and 10361D (PLA 10), machined with Drill-A at cutting speed equal to 20 m/min, and feed rate equal to 0.03 (Fig.10a) and 0.12 (Fig.10b) mm/rev respectively. It is clearly observed the enhanced hole surface quality with the increment of the feed rate.

Drilling of conventional composites requires low values of feed rate while biocomposites can be drilled with higher feed rates leading to better hole surface quality. These results can help to reduce the cutting time and in consequence the energy consumption and cost of drilling operations in biocomposites.

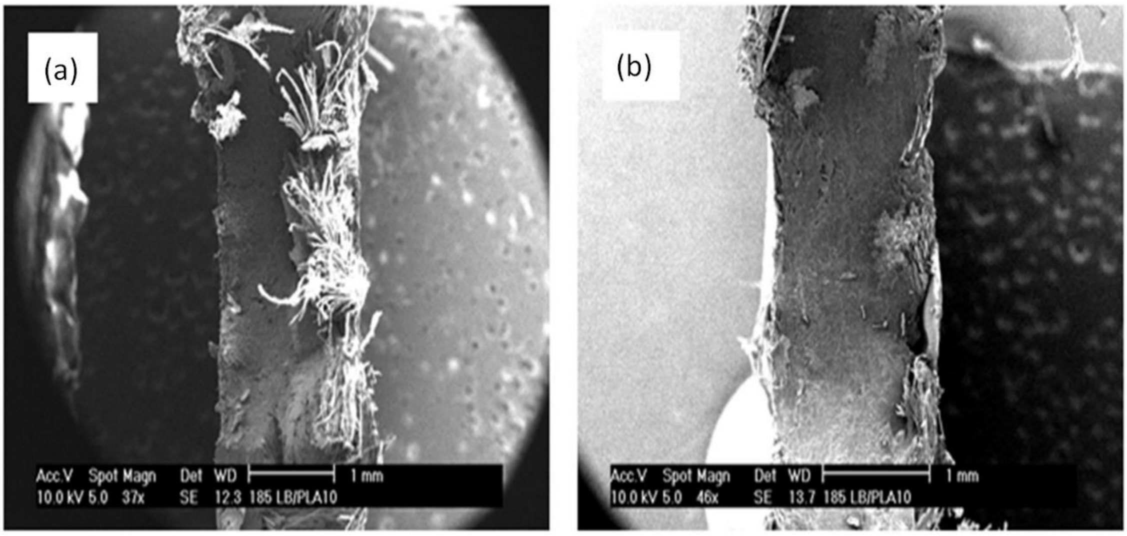

Figure 10. SEM- EDS image of transversal section of the drilled hole (biocomposite basket weave flax (BF) and 10361D PLA made of 2 layers), drilled with drill-A at cutting speed 20 m/min and feed rate 0.03 mm/rev (a) and 0.12 mm/rev (b) respectively.

3.2.Drill diameter

Drill diameter was analysed through the results obtained from tests 28-33. Two materials consisting of four layers were tested: basket (2x1) weave cotton (BC) and basket (2x1) weave flax (BF) combined with 10361D PLA matrix. Both materials were drilled with drill-A with three different diameters equal to 3, 5 and 6 mm respectively. Constant cutting speed equal to 20 m/min and feed rate equal to 0.06 mm/rev were established.

Fig.11 shows that push out damage increases in absolute terms with drill diameter during the drilling of biocomposites reinforced with basket weave flax fibres. However, the damage factor (ratio between diameter of damaged are and nominal diameter) is similar (around 1.1) in the range of diameters analysed. Similar results were obtained when analysing peel up damage extension in the case of testing cotton fibres biocomposites, see Fig.12. Both peel up and push out increase slightly with drill diameter in absolute terms however the damage factor is similar. Thus the influence of drill diameter can be neglected comparing with the influence of other cutting parameters as feed rate or cutting speed.

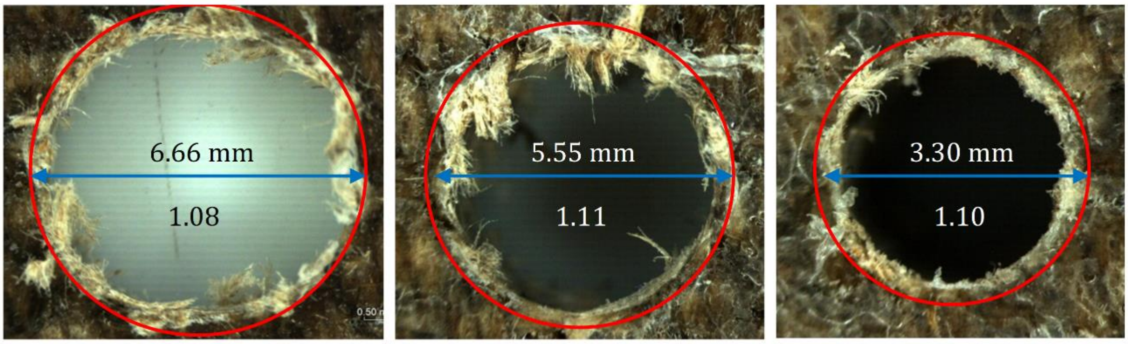

Figure 11. Hole quality (in terms of push out damage) of basket weave flax (BF) drilled by 3, 5 and 6 diameter drill-A.

3.3.Plate thickness

The influence of the composite thickness on resultant damage was analysed for the cases corresponding to basket weave cotton (BC) and the basket weave flax (BF) with 10361D PLA matrix, being both composites manufactured with 2, 3 and 4 layers and drilled with Drill-A and Drill-B and diameter equal to 6 mm. Cutting speed equal to 20 m/min and feed rate equal to 0.06 mm/rev were established. Results of tests denoted 3, 13, 26-29 in Table 3 were compared for this analysis. Resulting damage factor (push out and peel up) are presented in Fig.13, showing that drilling induced damage increases with the number of layers. It should be noticed that the maximum thickness analysed was 2.85 mm, thus all specimens can be considered thin laminates. Damage factor increases with plate thickness in the analysed range.

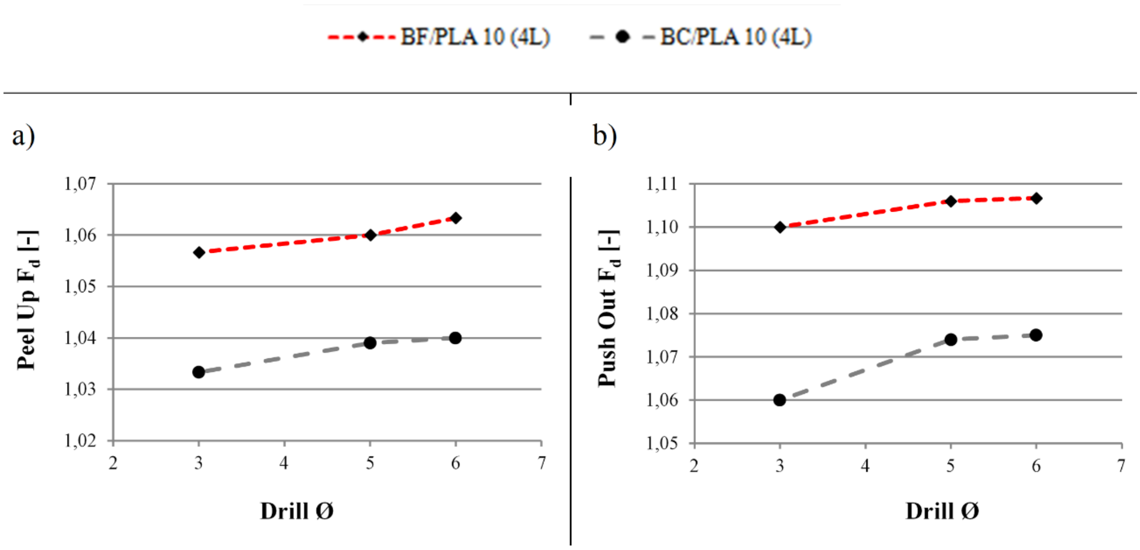

Figure 12. Peel up and Push out damage factor vs drill diameter (drill-A). Basket weave flax and cotton fibres with PLA10 matrix.

3.4. Drill geometry

The analysis described in previous sections have demonstrated that in general, the damage induced by drill-B (80º) was found to be lower than that produced by drill-A (118º). This behaviour is due to the lower value of drill point angle, also related to decreased damage extension in conventional composites, see for instance a recent work of the authors [11].

Fig.6 shows that induced damage using drill-A is greater than that obtained with drill-B for different materials and cutting speed. Nevertheless, the sensibility of damage generation with drill point angle is not the same for all materials involved in the study and depends on the nature of the reinforcement. In the case of biocomposites reinforced with basket weave flax, damage factor was reduced from 1.11 to 1.06 using drill-B instead of drill-A. On the other hand, the reduction of damage factor in biocomposites reinforced with cotton was almost negligible.

The results shown in Fig.8 confirm that damage factor is reduced using drill-B for different materials and feed rates. Fig.13 shows that drill-A leads to greater induced damage factor for different thicknesses, demonstrating the importance of selecting proper drill geometry in order to minimize damage extension. Drill sharpness is a key parameter influencing damage extension. Thus the selection of low drill point angle can help to obtain better results without incrementing cost or energy consumption.

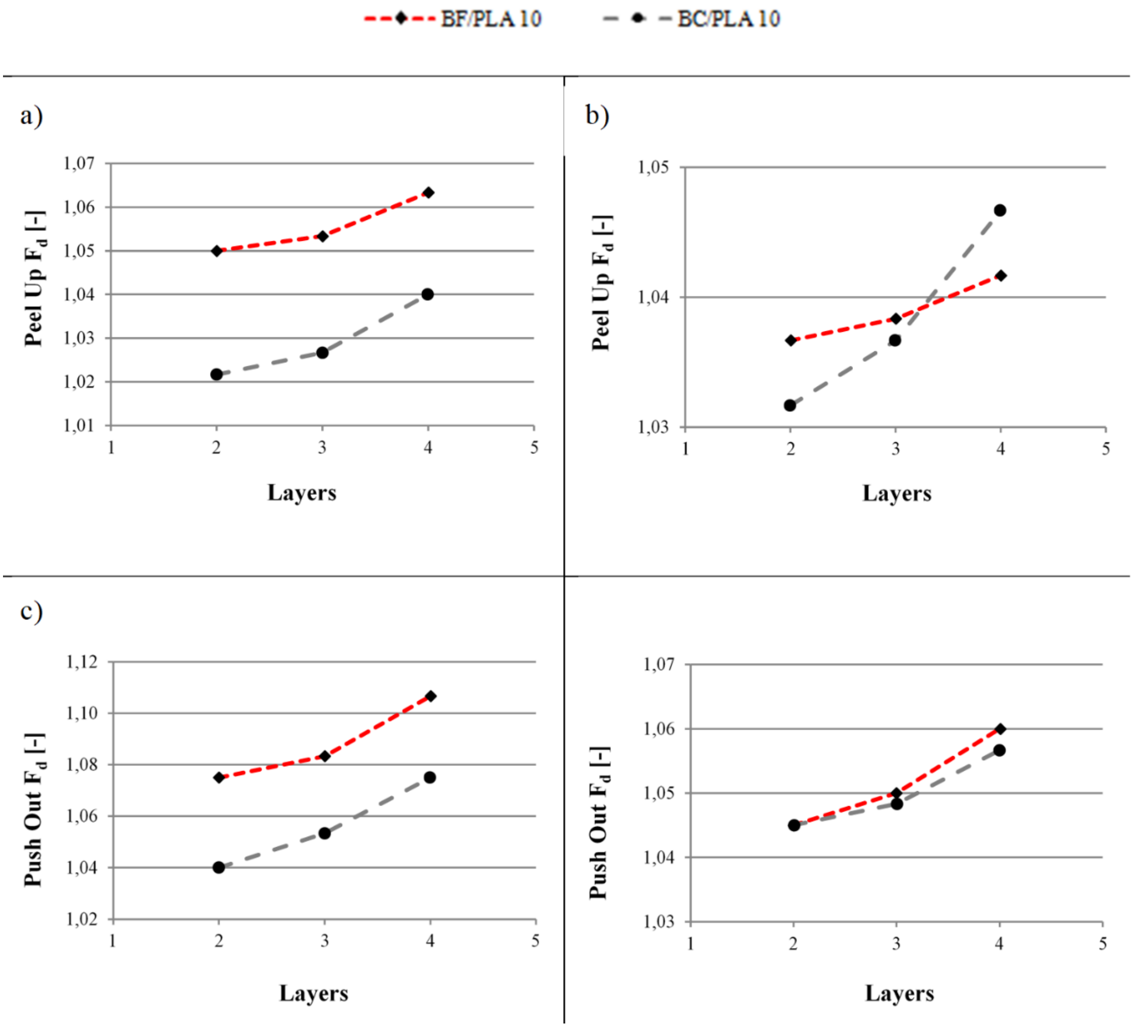

Figure 13. Damage factor vs number of layers for the composites BF/PLA10 and BC/PLA10. a) Peel up obtained with Drill-A, b) Peel up obtained with Drill-B, c) Push out obtained with Drill-A and d) Push out obtained with Drill-B.

3.5. Type of biocomposite

Fig.14 shows a comparison of the push out damage produced for the five materials analysed made of two layers: basket weave flax and 3260HP PLA matrix (BF/PLA 3);

basket weave flax and 10361D PLA matrix (BF/PLA 10); plain weave flax (PF/PLA10); plain weave jute (PJ/PLA10); and basket weave cotton (BC/PLA10). These tests were conducted at a cutting speed equal to 20m/min and feed rate equal to 0.06 mm/rev, corresponding to tests denoted 5, 10, 15, 20, and 25 in Table 3.

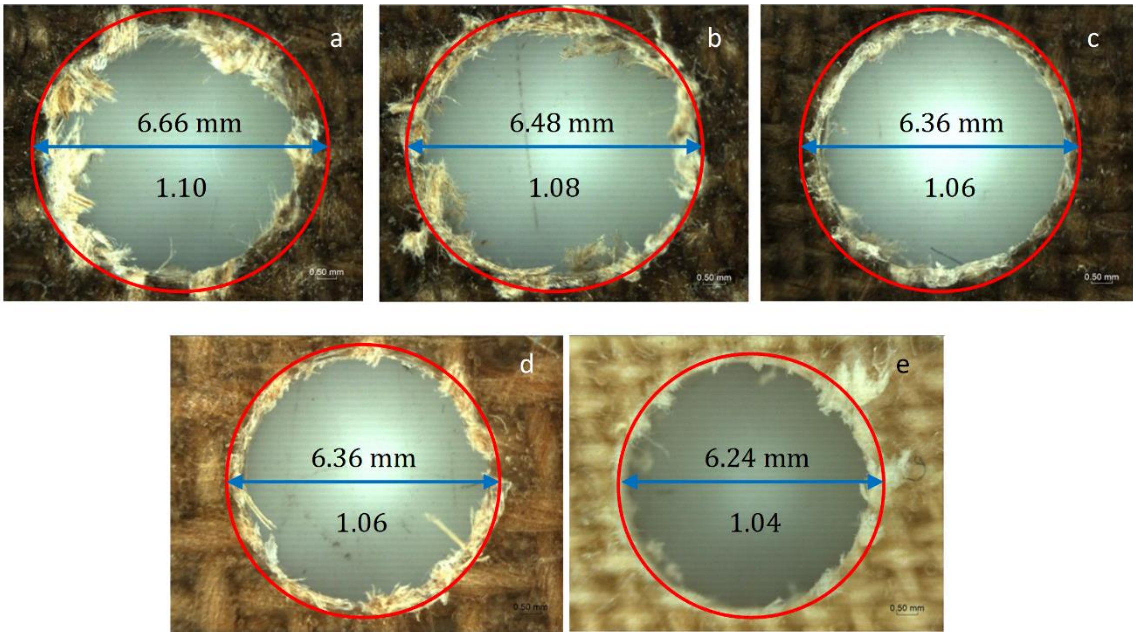

Figure 14. Push out induced damage obtained with Drill-A (2 layers, cutting speed 20 m/min, feed rate 0.06 mm/rev) in the five composites analysed: a) Basket weave flax with 3260HP PLA (BF/PLA 3); b) basket weave flax with 10361D PLA (BF/PLA 3); c) plain weave flax (PF/PLA10); d) plain weave jute (PJ/PLA10); e) basket weave cotton (BC/PLA10) from left to right and up to down.

The lowest values of damage factor were found in the case of cotton based biocomposites, while the highest damage factor was found for basket weave flax (BF) using the 3260HP PLA. The influence of fibre material on damage factor can be related to the biocomposites tensile strength. An inverse relation between the tensile strength, see Table 2, and damage factor was found. Flax based composites show the highest tensile strength and also the highest damage factors. This relationship can be explained considering that higher tensile strength lead to higher cutting forces and, consequently, if cutting forces increase there is an increment in the damage factor. Nevertheless, the damage induced during drilling can also be influenced by the interaction between PLA and the different natural fibres used as reinforcement, this effect can be analysed in further researches.

Induced damage is lower in cotton and jute based biocomposites due to their lower tensile strength. However, different results were found comparing peel up and push out damage factors. In the case of peel up, induced damage for cotton was lower than for jute fibres (see Figs. 6 and 8), while push out damage factor is lower in the case of jute composite.

Concerning the influence of the matrix, damage factor in the composites manufactured with 101361D PLA, considering both peel up and push out, is lower than that observed in the composites based on 3260HP PLA. Fig.15 shows a comparison between the induced damage produced in a composite made of 3260HP and 10361D matrices. The polymer 10361D PLA is specifically designed as a binder of natural fibres and gives better interface cohesion resulting in reduced fraying.

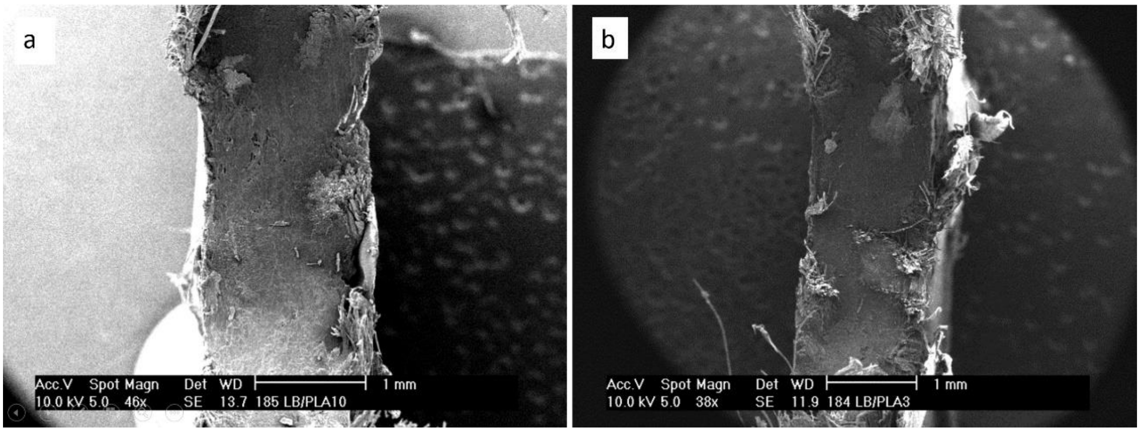

Figure 15. SEM- EDS image of transversal section of the drilled hole, drilled with Drill-A at 20 m/min cutting speed and 0.12 mm/rev feed rate, basket weave flax (BF) made of 2 layers and 3260HP PLA (a); 10361D PLA (b) respectively.

4. Conclusions

In this paper drilling operation of fully biodegradable composites based on natural fibres is analysed identifying fraying as the dominant damage mechanism while delamination was found to be negligible. Damage factor (defined as the ratio between diameter of damaged area and hole nominal diameter) both at hole entry (peel up) and exit (push out) was analysed for different cutting parameters, drill diameter, thickness, fibre material and matrix.

Concluding remarks are summarized below:

- The increase of both cutting speed and feed rate caused a decrease in damage extension. The increment of biocomposites stiffness with strain rate causes a more brittle behaviour for high feed rate and cutting speed leading to a cleaner breakage of fibre and in consequence, decreased fraying.
- The drill point angle was found to be an influencing geometrical parameter: the lower the drill point angle the lower the damage extension. This is key result when selecting proper drills for holes machining.
- It was found negligible influence of drill diameter, while damage factor increases with plate thickness.
- The damage extension was found to be dependent also on the fibre type. Induced damage is lower for cotton and jute based biocomposites due to their lower tensile strength.
- The matrix based on polymer 10361D PLA, owing the better interface cohesion, resulted in reduced fraying.

The present study shows the importance of controlling process parameters and material constituents in order to limit damage extension, giving valuable information for increasing the industrial use of natural fibre fully biodegradable composites.

These results can be considered the starting point for future research in this field. There are numerous interesting studies that must be conducted to get a better understanding of the influence of the induced damage during drilling on the residual properties of the drilled specimen. Some of these future works are the study of the residual tensile strength, residual flexural strength and fatigue behaviour.

Acknowledgements

Authors acknowledge the financial support of Spanish Ministry of Economy and Competitiveness under the project DPI2013-43994-R.

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